ETFE FOIL CUSHION TECHNOLOGY FOR CRUISE LINERS

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Summary

AIDA Cruises, the German-Italian subsidiary of the American shipping company Carnival Corporation, has one of the world's most modern and most environmentally friendly fleets of cruise liners. The name AIDA suggests visits to other cities and countries, dream holidays, relaxation and experiencing nature on the very highest level.
The AIDAprima and its sister ship the AIDAperla are two new Hyperion Class cruise liners that have now entered service. Both ships were built at the Mitsubishi Heavy Industries ltd. (MHI) shipyard in Nagasaki, Japan.
The total area of the ETFE roofs on both ships is about 4,000 sqm. Three-layer, transparent ETFE foil cushions span over the pool and leisure areas of the activity decks with their "4 Elements" and "Beach Club" centrepieces. Movable roof sections enable the areas of the "4 Elements" to be opened to the sky.
Vibrations from the ship's engines, acceleration forces due to the motion of the ship, high wind loads some 50 m above sea level, the marine climate with its corresponding salt concentrations plus the different climate zones place tough demands on the materials and combinations thereof as well as the structural design and the detailing. ETFE foil roofs in shipbuilding are new, which is why the necessary engineering solutions represent a huge challenge.

1. INTRODUCTION

For the first time on cruise liners, two large upper deck areas have been roofed over with transparent ETFE foil domes (Fig. 1). A total of 82 three-layer, transparent foil cushions with printed areas cover the steel frames of the “Four Elements” (Fig. 2) and “Beach Club” (Fig. 4) domes – a roof area of almost 2000 m² per ship. Beneath the foil domes there are extensive pool and leisure areas with bars, waterslide and climbing course.

Fig. 1: The upper decks of the AIDAprima with the two foil domes “Four Elements” and “Beach Club”; 3D computer image, copyright: AIDA CRUISES, Rostock, PSD, Hamburg

The “Four Elements” dome is composed of two movable halves so that – depending on weather conditions – it can be opened to allow crew and passengers to enjoy the fresh sea air or closed to protect against wind and rain while enjoying the pool facilities (Figs. 2 and 3).

Following extensive studies and investigations, the designers at Hamburg-based Partner-ShipDesign (PSD) and the AIDA Cruises shipping company in Rostock opted to use ETFE as the roof covering – a new material on cruise liners – because it offers a number of advantages compared with the designs in laminated safety glass used up until now:

- lower weight per unit area
- larger support spacing (lower self-weight, greater transparency)
- lower system stiffness
- higher UV transmission

The weight per unit area of the three-layer ETFE foil cushions (with thicknesses of 250, 200 and 250 µm) is less than 1.5 kg/m². A corresponding laminated safety glass roof would weigh at least 20 times this figure.

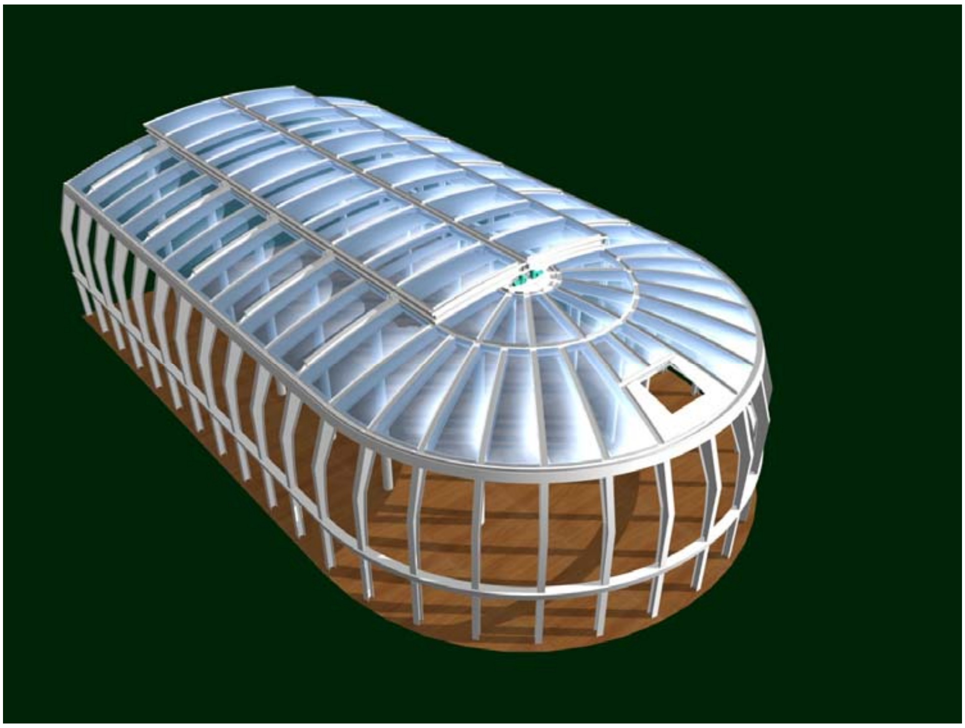

Fig. 2: The “Four Elements” foil dome when closed; 3D computer image, draft design, seele cover

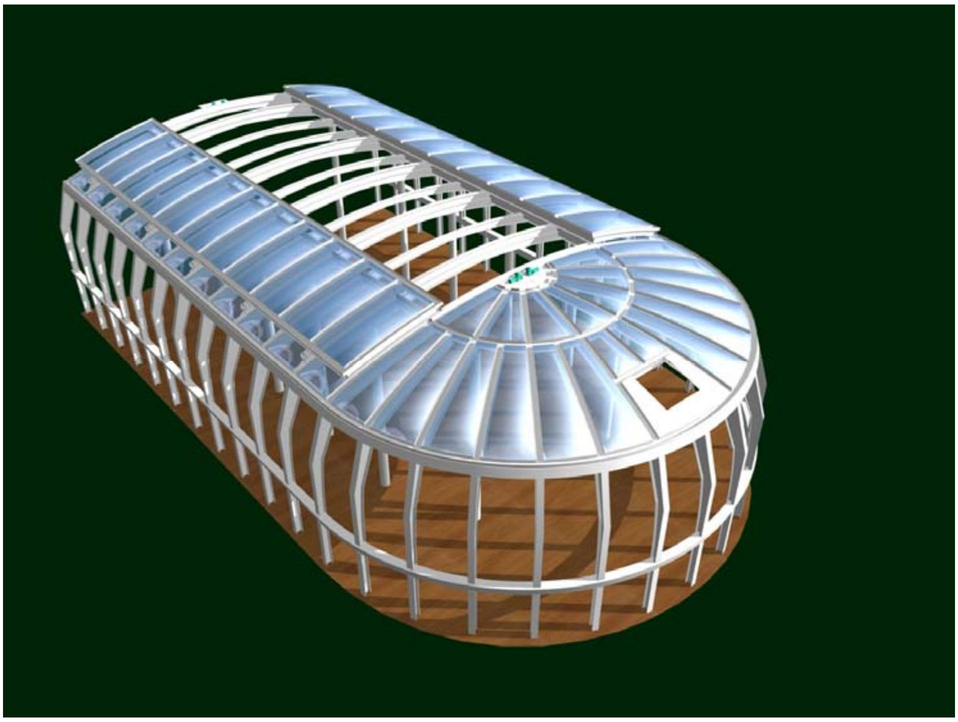

Fig. 3: The “Four Elements” foil dome when open; 3D computer image, draft design, seele cover

The span of the ETFE foil cushions achieved here is, on average, about 2.5 m between the curved members of the steel frame. The longest ETFE cushions on the “Beach Club” roof are about 33 m long. Linear support to panes of laminated safety glass would require a steel member every 1.2 m. So compared with glass, ETFE is an advantage when it comes to transparency and weight of the structure. Moreover, the low system stiffness of the ETFE foil cushions turned out to be another benefit. They are forgiving when it comes to larger deformations of the structure which result from the motion of the ship (hogging, sagging, etc.) and temperature fluctuations. Finally, on the “Beach Club” structure the shipbuilders managed to avoid load bearing members parallel with the longitudinal axis of the ship, so the uniform appearance of the soffit is not interrupted by any longitudinal members (Fig. 4). Another aspect in favour of ETFE foil is its high UV transmission. An ETFE roof favours the growth of plants underneath – an important criterion for leisure areas with natural flora (and fauna).

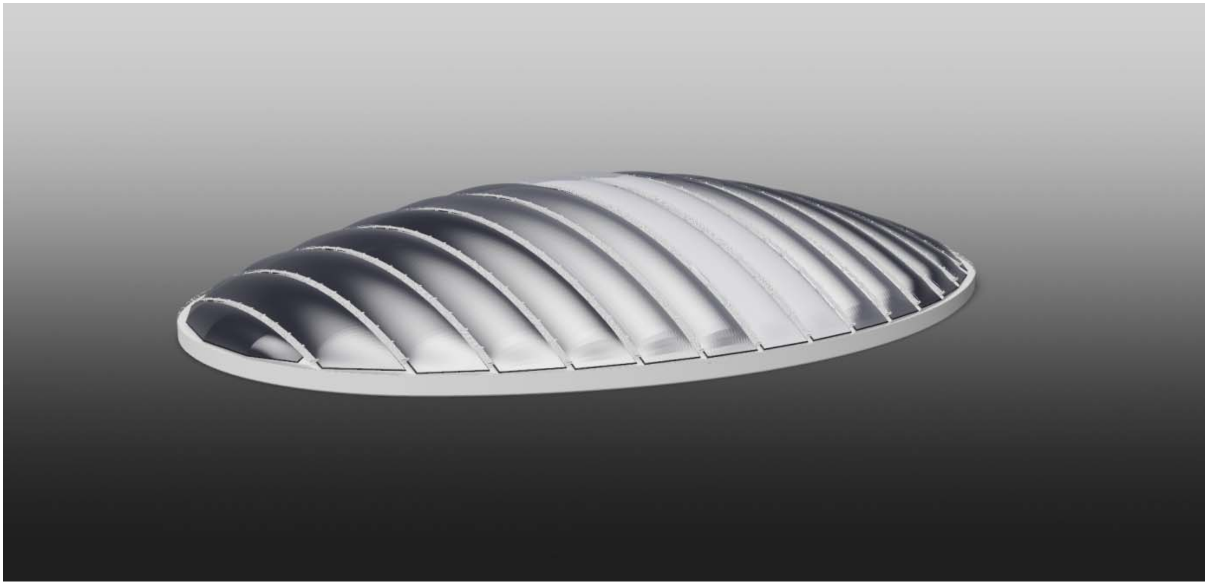

Fig. 4: The “Beach Club” foil dome; 3D computer image, draft design, seele cover

2. DESIGN

seele cover was appointed by the Mitsubishi Heavy Industries (MHI) shipyard in 2013 to carry out a design and build contract for a total of four ETFE foil roofs on the two cruise liners. The contract included very different types of work:

- ETFE foil cushions with clamping plates and temporary protection measures during construction.
- Air supply systems, including fan units, supply lines, power chains and pressure instrumentation.
- Gutter systems with foam glass insulation and waterproofing-sealing of the surfaces.
- A ventilation element in the “Beach Club” dome and movable roof segments in the “Four Elements” dome, including the necessary electrical installation, sensors, control system, remote controls, geared motors, belt drives, lip and pneumatic seals and pneumatic locking devices.

- Mobile maintenance bridge
- Mock-ups in Japan and Germany
- Design concept for GFRP open-grid flooring for maintenance walkways, with steel supports
- Design concept for external washing systems for both domes
- Design concept for fall protection systems with fixings
- Design concept for primary load bearing structure in steel (Figs. 5 and 6)

The upper decks of cruise liners represents a new application for ETFE foil cushions and this led to special requirements that do not normally have to be considered for structures on land.

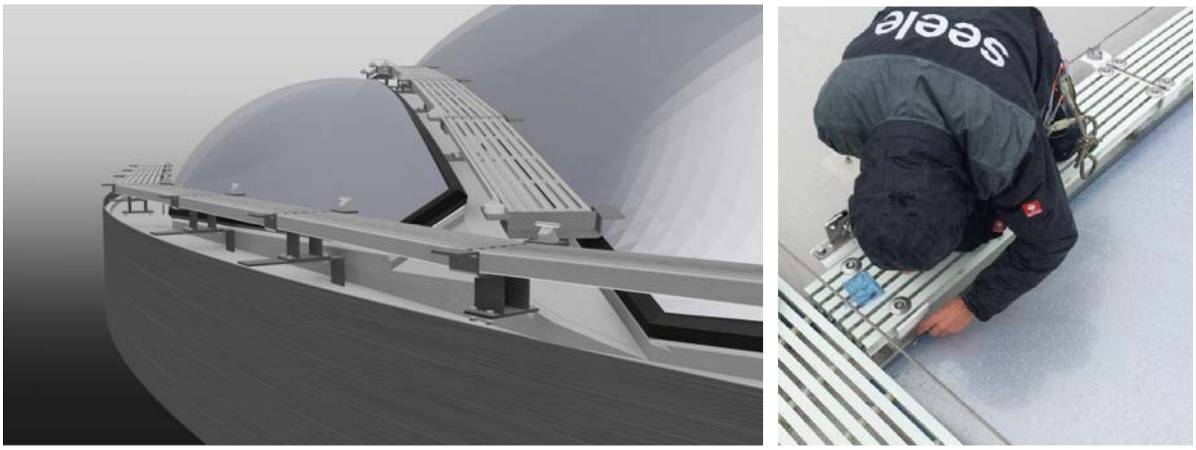

Fig. 5: “Beach Club” foil dome, isometric view showing GFRP walkway and ETFE cushion connection; 3D computer image, draft design, and picture from the installation process, seele cover

2.1 Shipbuilding specifications

The directives and codes of practice applicable in shipbuilding are in some instances very different to those that apply to buildings. For obvious reasons, on ships there are very stringent requirements covering fire protection, emissions of hazardous substances and potential noise and vibrations and their possible effects (sound transmission, fatigue strength and fixing of components).

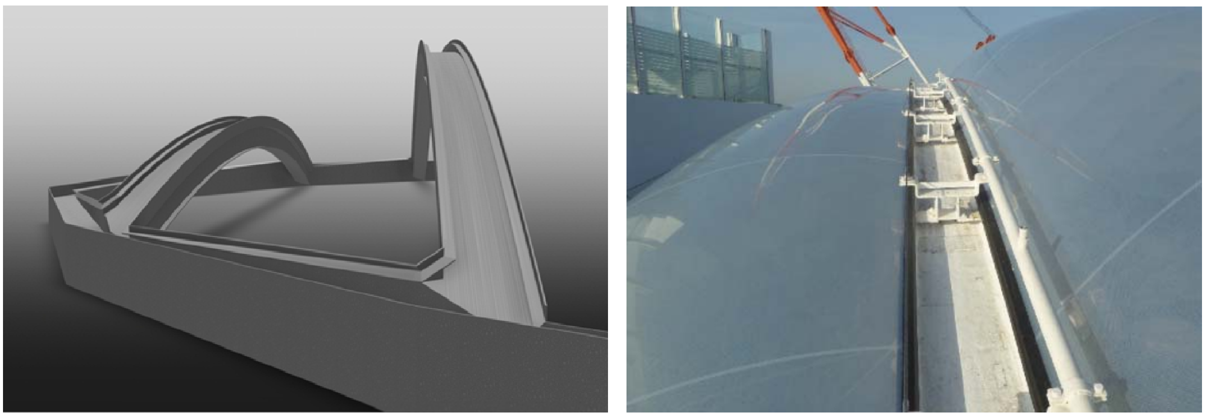

Fig. 6: “Beach Club” foil dome, detail of steelwork connections; 3D computer image, draft design, and picture from the installation process, seele cover

Load assumptions and structural safety concepts are especially important in shipbuilding. The design code normally used for buildings in Europe, Eurocode (EC) 0, Basis of structural design, is not generally applied in shipbuilding, likewise the (semi-)probabilistic safety concept of partial safety factors for actions and resistances associated with this standard.

2.2 Corrosion protection

The salt-laden marine climate places high demands on the corrosion resistance of metal components and their connections. However, the requirements are known from building in corrosive environments on land (coastal areas, swimming pools, saltwater baths). In this respect, the classification company (e.g. DNV GL) offers comprehensive and helpful rules and specifications in its directives.

Retaining members in the form of clamping plates made from aluminium are normally used along all the edges of the textile or foil membranes of membrane structures. Such clamping plates are usually connected to the primary structure, e.g. in steel, by means of (stainless steel) screws or bolts.

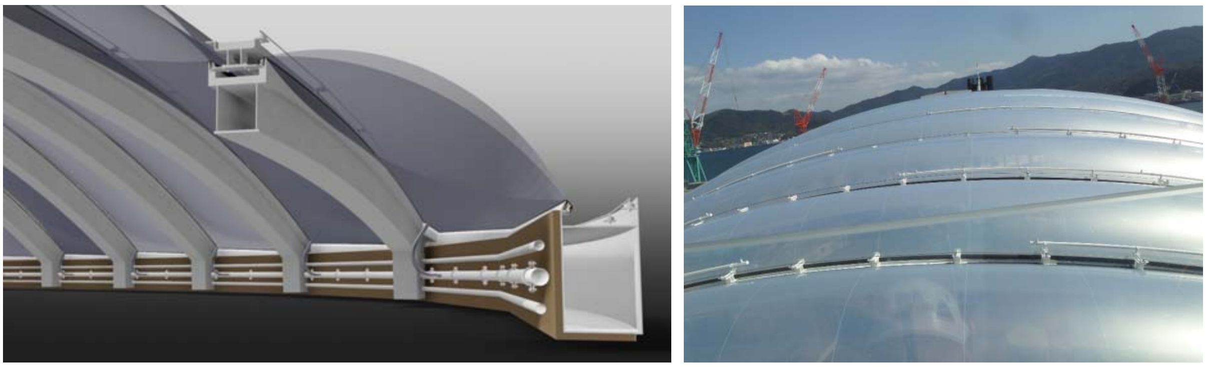

Fig. 7: “Beach Club” foil dome, steel sections with thermal insulation and services; 3D computer image, draft design, and picture from the installation process, seele cover

Such connections consist of three different metals: steel, aluminium, stainless steel. If the different metals are not kept apart by separating membranes, there is a great risk of galvanic corrosion. seele cover has therefore developed a clamping plate specifically for use in corrosive environments. The patented aluminium section does not need any screws because it clips onto the painted mild steel of the primary structure. A separating layer made from EPDM prevents galvanic corrosion between the anodised aluminium and the painted mild steel (Fig. 8).

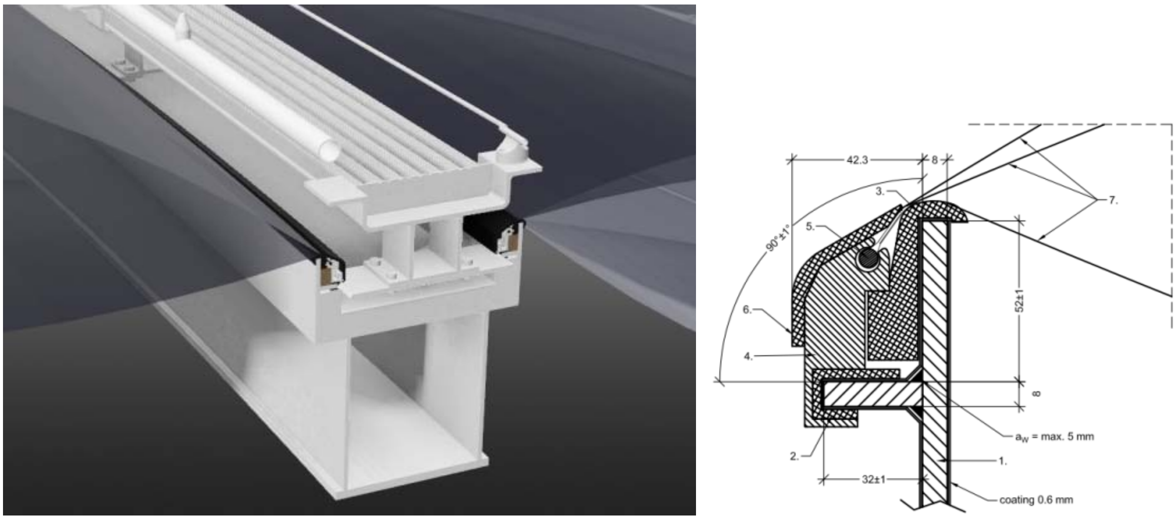

Fig. 8: “Beach Club” foil dome, gutter cross-section with thermal insulation; 3D computer image and detail drawing, draft design, seele cover

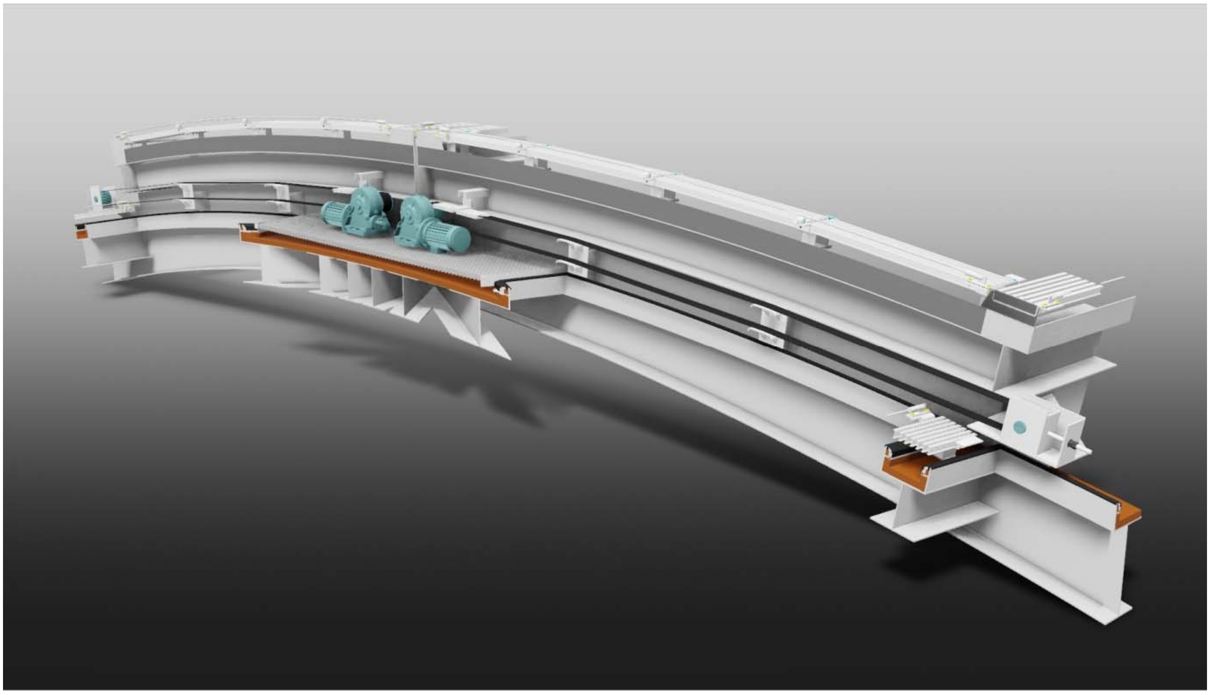

Fig. 9: “Four Elements” foil dome, drive mechanism for movable roof segment; 3D computer image, draft design, seele cover

2.3 Vibrations, noise

Minimising vibrations is not only a vital criterion for comfort on board a cruise liner. In extreme cases, even safety can be affected.

Of course, on the one hand, noise or vibrations should not have any unnecessary or unacceptable effects on passenger operations. On the other, a ship is a means of transport, which obviously involves adverse effects due to its motion and engines. On ships, vibrations and noise can be caused by, for example:

- ship's engines
- waves
- motion of the ship
- deformations of the ship
- equipment (drive mechanisms, motors, fans, air conditioning, etc.)
- flow noises from air ducts

Specific measures must be employed to deal with the above:

- avoiding natural frequencies and brittle failure of important or load bearing components (fatigue strength).
- use of vibration-cushioned fixings for components.
- acoustic insulation and suitable supports for installations, equipment, fans and drive mechanisms (Figs. 9 and 10).
- adequate sizing of air ducts and fans.

seele cover, for example, has fitted the acoustic-insulated fans with damped bearings, increased the sizes of air supply lines beyond the actual flow requirements and installed low-vibration fixings for components.

2.4 Temperature and humidity fluctuations

The transparent domes of the upper decks on both cruise liners have been fitted with thermal insulation for the first time. However, the members of the project team agreed that owing to the many openings and seals (windows, doors, movable roof segments), avoiding all local thermal bridges would result in excessive costs. Furthermore, as the geographic location of the ship changes constantly and not all the cruise routes could be defined exactly beforehand, the actual temperature differences (inside/outside) that would actually occur could only be specified roughly in advance.

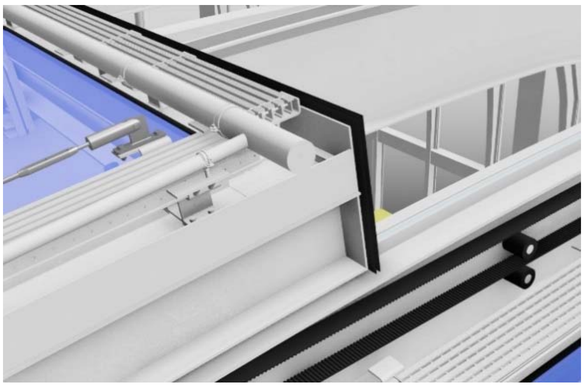

Fig. 10: "Four Elements" foil dome, movable roof segment sealed with pneumatic seal plus additional lip seals; 3D computer image, draft design, seele cover

With such boundary conditions, in certain climatic conditions (temperature gradient and humidity) there is still a certain risk with regard to local and temporary condensation, especially on the steel components. Any condensation that does occur can be minimised or even totally avoided by temporarily increasing the flow velocity of the circulating interior air. The distribution of the air in the two domes by the air-conditioning system (which is required anyway) should achieve the desired effect.

2.5 Loading assumptions

As mentioned above, the geographical location of the ship changes and so – unlike for buildings on land – the load assumptions cannot be defined according to the location. Instead, they must be prescribed on the basis of the empirical figures of the ship's owner and the recommendations of the classification company (in this case Germanischer Lloyd, now DNV GL). The load cases for the (quasi-)static design of the ETFE foil domes are made up of the following actions:

- dead loads
- wind loads
- snow loads
- vibrations
- acceleration forces (motion of the ship)
- restraint forces (ship deformations, temperature)

2.5.1 Dead loads

The weight of the structure plays a major role for ships. In particular, the weight of components that are located high above the waterline, e.g. steel domes on upper decks, should be kept as low as possible.

As rigid frames are frequently used on ships, the self-weight of the steel structure converted into a weight per unit area is about 60–80 kg/m², depending on the loads to be considered and the type of structure (planar or curved, space frame, etc.). This also roughly matches the weight of conventional dome structures in steel which are glazed with laminated safety glass.

However, the self-weight of ETFE foil cushions, including their clamping plates, is less than 5 kg/m². That is only about 10% of the weight per unit area of overhead glazing in laminated safety glass, with the associated shorter spans of the glass panes between the steel members of the primary structure. So the use of ETFE foil cushions considerably reduces the dead loads on the upper decks.

Besides the self-weight of the structure, the loads of items fixed to the structure, which can amount to 30 kg/m² or more, must also be considered; e. g. loudspeakers, lighting, stage equipment, water-filled sprinkler pipes, waterslides, climbing courses, fall protection systems or also roof and façade washing installations.

2.5.2 Wind loads

The MHI shipyard appointed Rostock-based engineers Motoren- und Energietechnik (MET) GmbH to determine the wind loads on the foil roofs.

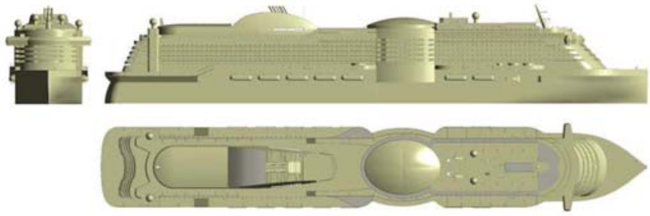

Fig. 11: 3D model of ship for CFD simulations; MET on behalf of MHI

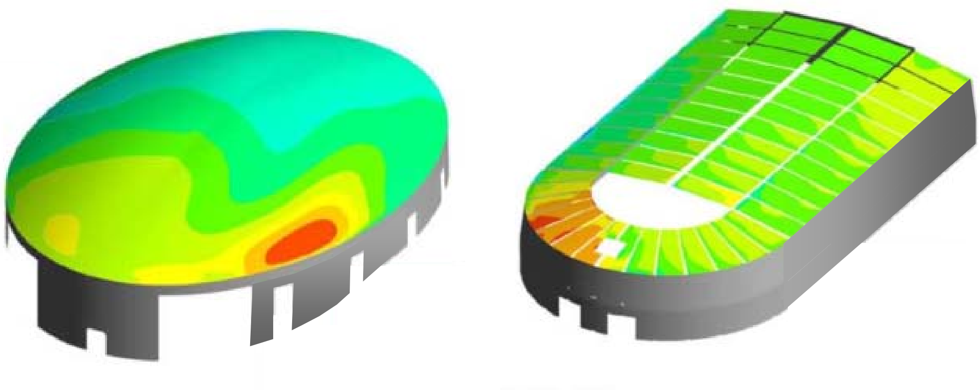

Fig. 12: CFD simulations of wind loads on both foil domes; MET on behalf of MHI

The CFD simulations (CFD = computational fluid dynamics) carried out by MET were based on a design wind speed of 56 m/s, which corresponds to 201.6 km/h. In the computer this wind speed was applied to the 3D model of the ship in 45° steps over its full height (Figs. 11 and 12). The results show that the foil domes at a height of about 50 m above sea level are primarily subjected to symmetrical wind suction actions.

The fact that only low wind pressures and hardly any asymmetrical wind loads occur on the upper decks is obviously due to the high and dominant hull of the ship, which rises above the waterline like a wall, and the relatively shallow form of the ETFE foil domes. In order to be able to check the stability of the load bearing structure for non-uniform wind loads as well, the wind suction loads determined were applied not only symmetrically (all sides), but also asymmetrically (one-sided).

2.5.3 Snow loads

Of course, quite different snow loads can occur depending on whether the ship is cruising through the Caribbean or in polar regions. Taking into account the recommendations of the classification company (in this case Germanischer Lloyd, now DNV GL), a design snow load of 1.5 kN/m² was assumed for the ETFE foil roofs on these ships. Assuming a snow density of 300 kg/m³, this would correspond to a constant snow depth of 50 cm over the entire roof.

2.5.4 Acceleration forces

The motion of the ship can lead to acceleration forces that act on the structure, items fixed to the structure and any snow loads on the roof. Acceleration forces can be reduced to three translational and three rotational ship movements:

translational motion

- surging (motion along the longitudinal axis)
- swaying (motion along the transverse axis)
- heaving (motion along the vertical axis)

rotational motion

- rolling (motion about the longitudinal axis)
- pitching (motion about the transverse axis)
- yawing (motion about the vertical axis)

The acceleration forces result from the specification of the ship, which was drawn up by the owner taking into account the guidelines and recommendations of the classification company (in this case Germanischer Lloyd, now DNV GL).

2.5.5 Restraint forces

The load bearing structure of the foil domes can be subjected to restraint forces caused by deformations of the ship or temperature fluctuations.

Restraint forces due to deformations of the ship can occur when the ship's hull bends upwards on the crest of a wave (hogging) or, correspondingly, bends downwards in the trough of a wave (sagging). The magnitude of the forces acting on a component depends on various factors, e.g. the stiffness of the hull, the distribution of stiffness and hence also the location of the component on the ship.

Temperature fluctuations impose restraint forces on a component when its expansion is hindered. This is especially the case for structures with multiple degrees of static indeterminacy (with fixity and rigid connections), which are frequently used in shipbuilding.

The ship deformations to be assumed in the calculations and the temperature ranges to be considered likewise arise out of the specification for the ship.

2.5.6 Vibrations

A modal analysis is carried out to assess whether the load bearing structure of the respective dome is susceptible to vibration. This analysis is initially based on masses estimated as accurately as possible, but on calculations of the masses in later phases of the design.

The modal analysis includes the numerical characterisation of the dynamic behaviour of load bearing structures with the help of vibration figures, i.e. the modal parameters natural frequency, modal form, modal mass and modal damping. Defined frequency ranges for structural vibrations must be avoided in order to avoid resonances with the excitation frequencies (first and second order) of the ship's propellers.

It can be seen that the weight of the structure must be ascertained as quickly and accurately as possible because all design steps and calculations depend on the masses and the distribution of those masses over the ship. Those masses in turn depend on the external loads (wind, snow, etc.). The significance of the loading assumptions for the structure, and hence the weight of the structure and the costs, is frequently underestimated – in shipbuilding just as much as for buildings on land. That also applies to the work involved in determining the loading assumptions as carefully as possible.

2.6 Installation

Installing ETFE foil cushions on board a ship can be very different to conventional erection work for a similar assembly on land. Some of those aspects are:

- parallel working on several levels (suspended scaffolds, safety nets, fall protection); safety nets may not be permitted (Japan).
- narrow access to working areas, confined working spaces, limited crane times and restrictions on storage and floor space on board.
- possibly interim storage of materials and tools in the shipyard.
- more stringent demands regarding fire protection (also during erection).
- different tolerances in shipbuilding (structural steelwork).
- follow shipbuilding and shipyard rules and regulations.
- necessary particular protective measures for any subsequent painting and welding work required on site (steel and aluminium structures).
- corrosive environment (marine climate, salt-laden air), possibly corrosive mists in the air (paints, solvents, filler metals).
- possible downtimes due to poor weather (“typhoon season”, work outdoors).

Fig. 13: ETFE foil cushions being installed on board the AIDAprima, MHI shipyard; seele cover 2015

2.7 Design and documentation

In a design and build contract the many different types of work involved (steelwork, ETFE cushions, fan units, air supply lines, sensors, power chains, safety system, washing installation, drive mechanisms, maintenance walkways, motors, controls, pneumatic seals, etc.) must be coordinated with each other in terms of materials, architecture, construction and structural analysis in order to achieve a coherent and functioning overall concept. This represents a great challenge and entails a great deal of planning work.

In this project the draft, detailed and fabrication planning work was carried out internally in three planning phases. The approval work was carried out by the institutions of the respective classification company (class) and country of registration (flag). The approvals of further institutions involved (US Coast Guard etc.) were obtained by the shipyard during the planning process. As ETFE foil cushions are being used on a cruise liner for the very first time, the planning work represented a new departure in membrane construction which has enhanced the range of experience of seele cover.

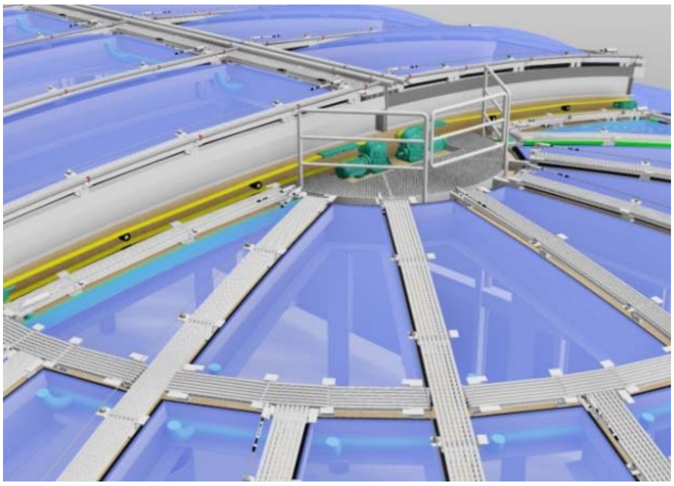

Fig. 14: Isometric view “Four Elements” foil dome; draft design, seele cover 2013

If a problem occurs, the ship is somewhere at sea, and so it should be possible for the crew to rectify the problem themselves if at all possible. As a result, the accuracy and succinctness of the operating instructions are crucial factors. Therefore, if possible, the designers should consider in advance which defects could possibly occur and how the crew could deal with these. Some work can, should or may only be performed by trained specialists or only by the company that carried out the work in the first place. It is also vital to carry out maintenance of the structure regularly in order to prevent problems and potential secondary damage. It was important to consider which inspection and maintenance measures could be carried out by the crew and which only by the company responsible. This is regulated by a detailed checklist with information on the respective inspection and maintenance intervals.
Some contractors might already be dreaming of a two-week maintenance or erection contract on the AIDAprima when it is anchored somewhere in the Caribbean!

3. RÉSUMÉ

With the international make-up of the project team, the long distances between design and building locations and also the complex works involved with the need to coordinate the many interfaces, the AIDA project placed great demands on all those involved. seele cover and its planning team were happy to rise to this challenge.